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13. ABSTRACT (Maximum 200 words)

The goal of this project has been to develop a new robust structural model that is being coupled with existing computational fluid dynamics (CFD) codes to accurately simulate the dynamics of parachute and parafoil systems. This research will allow the Army to reduce the time and cost of developing new airdrop systems and retrofitting existing systems for new applications. Parachute dynamics is an extremely complex process. This process is governed by nonlinear time-dependent coupling between the parachute and surrounding airflow and involves large canopy shape changes and unconstrained motion of the parachute in the fluid medium. To successfully simulate this complex process, a robust structural model is essential. The following capabilities were added to the structural model: (1) membrane wrinkling, (2) material orthotropy, (3) local bending and damping elements, (4) user-defined time-dependent element properties, (5) various nonlinear transient solution algorithms, (6) approximate fluid forces, (7) stress projection algorithms, and (8) local nodal coordinate systems. It has been demonstrated that large scale finite element modeling of parachute dynamics is feasible using this structural model. Significant transfer of this basic research was accomplished. New structural model features have continuously been incorporated into a finite element code which has been used extensively by Army engineers to perform simulations of Army parachute systems.

14. SUBJECT TERMS

parachutes, computer simulation, finite element method

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## New Structural Model for Parachute Inflation Simulations

### 1. FORWARD

The deployment, inflation, terminal descent and landing of a parachute system are extremely complex aerodynamic phenomena. These processes are governed by nonlinear time-dependent coupling between the parachute system and surrounding airflow, large canopy shape changes, and unconstrained motion of the parachute through the fluid medium. Due to these complexities, parachute systems have historically been designed using a semi-empirical approach supplemented by extensive testing. This approach to design is time-consuming, expensive, and stifles innovation.

During the last decade, the demands placed on parachute designers have increased significantly. Payload costs have increased, mission requirements have become more stringent, and the flight testing needed to develop new systems have become more costly. In light of these demands, the traditional semi-empirical approach to design is inadequate.

Computational methods have the greatest potential for providing engineers with the necessary predictive tools for parachute design. Although numerous commercial finite element codes exist, these codes lack the theoretical robustness needed for parachute simulations. Furthermore, these codes are closed to the users and therefore can not be easily modified by the users for their specific needs.

In this research project, a new structural model has been developed for simulation of parachute dynamics. This model has been coupled with an existing Computational Fluid Dynamics (CFD) model to simulate the interaction between the parachute and surrounding air flow. The structural model has been incorporated into a computer code which is continuously tailored for parachute simulations. As a result, it has been demonstrated that computer simulation of parachute dynamics, despite its complexity, is a realizable goal. This capability provides engineers with a "virtual proving ground" to evaluate candidate systems and will ultimately reduce the time and cost of establishing reliable parachute designs.

## 2. TABLE OF CONTENTS



## 3. LIST OF APPENDIXES

- Appendix A: Selected Results from Numerical Simulations

## 4. PROBLEM STATEMENT

The primary goal of this project was to develop a robust structural model to accurately and efficiently simulate the dynamic behavior of parachute systems. To accomplish this, the following specific problems were addressed:

- Since parachute fabrics can not support compressive stresses, "wrinkling" occurs at the onset of compression. The effect of "wrinkling" on parachute simulations was examined.
- Parachute fabrics are orthotropic. The importance of orthotropy on parachute behavior was not known. An orthotropic material model was developed to investigate this.
- After the initial deployment and prior to inflation, the parachute is negligibly stressed and the behavior is highly transient. Several approaches were formulated to effectively stabilize the numerical solution during this phase.
- The most efficient and accurate nonlinear transient solution algorithm for parachute simulations is not known *a priori*. A suite of algorithms was developed to evaluate this.
- Parachute systems utilize several specific operations for control which dramatically effect their dynamic behavior. These include line length control and controlled disreefing. The ability to model these operations was developed and evaluated.
- The true behavior of parachute dynamics involves coupling between the parachute and surrounding air flow. A coupled solution, however, is considerably more difficult to perform than a stand-alone structural simulation. The ability to include approximate fluid forces in stand-alone structural simulations was developed and evaluated.
- In addition to the global dynamic behavior of a parachute system, canopy and cable stresses are also critical to design. A method to evaluate dynamic stresses in parachute systems was developed.
- Numerous parachute systems of practical interest possess cyclically symmetric geometry. Special techniques that account for this symmetry to reduce the computational requirements were developed.
- Transition of this basic research to address specific Army needs for parachute modeling was a continuous objective of this project.

## 5. SUMMARY OF RESULTS

The primary result of this research project is that large scale finite element modeling of parachute dynamics is feasible provided that a robust structural model is used [1]. Our structural model has been implemented in a computer code which is used extensively by engineers at the U.S. Army Soldier Systems Center (Natick) and is continuously tailored to address specific Army airdrop needs. The structural model can be used with existing CFD models, such as those developed by the Army High Performance Computing Research Center (AHPCRC) at Rice University, to perform fully coupled parachute simulations. In developing this structural model, the following specific results were identified:

- *Modeling the effect of "wrinkling" is essential in parachute simulations*:

  Three wrinkling algorithms which account for large deformations and orthotropic materials were formulated and implemented [2, 3, 4]. Alternate algorithms were investigated to provide a comparison between predicted results and computational efficiency. All the wrinkling algorithms effectively remove all compressive stress. Good agreement between the various algorithms was obtained.

  Results obtained with and without wrinkling were dramatically different. The inflated shape of a parachute obtained without wrinkling was intuitively incorrect, whereas the shape obtained with wrinkling was much more realistic. Investigation of the minimum principal stress obtained without wrinkling revealed large regions and time periods where large compressive stress exist which adversely effect the predicted shape. Results of several simulations with and without wrinkling are given in the Appendix.

  Comparison between numerical simulations and experiments of membrane wrinkling were performed at the South Dakota School of Mines and Technology [5, 6]. These experiments are extremely valuable for verifying numerical simulations since analytical solutions for wrinkling of membranes undergoing large deformation are not available.

- *Material orthotropy has a major effect on the predicted behavior*:

  Orthotropic material relations which account for large membrane deformation were formulated and implemented. A number of example problems were run which demonstrate the dramatic difference between isotropic and orthotropic material responses. Except for this work, no other research has addressed wrinkling of orthotropic membranes subject to large deformations in a rigorous manner [2]. A comparison of results for an isotropic and orthotropic membrane with wrinkling is given in the Appendix.

- *Special techniques are required to stabilize the numerical solution after initial deployment and prior to inflation when the parachute is negligibly stressed and the motion is highly dynamic*:

  Two approaches were developed to address this difficulty. The first was to implement time-dependent user-defined global damping. This allows the user to prescribe a global damping history which starts at a large value (to stabilize the solution) and decreases with time to a negligible value (so the global motion is not effected). This approach has been used extensively in simulations performed at Natick [7].

  The second approach was to formulate two new special elements, called "kink" and "fold" elements, which provide local damping at cable nodes and membrane edges, respectively [8]. Numerical tests demonstrated that these elements effectively stabilize the solution without adversely effecting the predicted global response and allow for an increased time step which significantly reduces the computational effort. A comparison of results obtained with and without these special elements is given in the Appendix.

- *For the majority of parachute simulations, implicit time-integration algorithms combined with an iterative equation solver was most efficient*:

  Three nonlinear transient solution algorithms were implemented in the structural code. The first uses implicit time integration with a direct equation solver and a band width minimization algorithm. The second is a conditionally stable explicit method. The third uses implicit time integration with an iterative equation solver [9]. The third was installed collaboratively with Natick engineers using an iterative solver developed by the AHPCRC at Rice University [10]. Results obtained using the three solvers on the same simulation showed excellent agreement.

  Through numerous simulations, it has been found that the third solver is most computationally efficient for parachute simulations. The only limitation of the third solver is that it requires diagonal dominance of the system matrix which is only violated in special cases, such as when general constraint equations are prescribed.

  Implementation of a band width minimization algorithm for the first solver significantly improved its efficiency [11]. Without additional modifications to the second solver, the critical time step needed for algorithmic stability is prohibitively small for typical parachute simulations.

- *It is possible to simulate typical parachute control operations and disreefing with the structural model.*

  User-defined time dependent cable length changes and cable failure were implemented in the structural model. These capabilities allow for simulation of parachute control operations and disreefing. Numerous simulations utilizing these capabilities have been performed which demonstrate their usefulness for parachute simulations [12]. Several results demonstrating these capabilities are given in the Appendix.

- *Development of approximate fluid forces allows for realistic simulation of parachute dynamics using only a structural model.*

  Aerodynamic drag on cables and payload masses undergoing large displacements was implemented in the structural model [7]. These effects, along with user-defined time dependent membrane pressure, allow for approximate modeling of fluid forces in a stand-alone structural simulation. Since structural simulations are considerably less difficult to perform than fully coupled simulations, this capability allows for rapid evaluation of a parachute's dynamic behavior.

- *Stress projection algorithms allow for dynamic evaluation and visualization of canopy stresses.*

  A stress projection algorithm for parachutes undergoing large displacements was formulated and implemented in the structural model. This algorithm is a generalization of those used for small deformation linear elastic problems [13]. The algorithm allows for dynamic visualization of canopy stresses which is critical for evaluation of parachute system performance.

- *For parachute simulations that are cyclically symmetric, the model can be reduced to a single section which significantly reduces the computational requirements.*

  Local nodal coordinate systems were formulated and implemented in the structural model. This capability allows for modeling an entire round canopy using a single gore [12]. Since typical round canopies consist of thirty to sixty-four gores, this capability significantly reduces the model size and solution time.

- *Significant transfer of the basic research performed under this project was accomplished.*

  New structural modeling capabilities have been continuously incorporated into a computer code which is used extensively by engineers at Natick to perform parachute dynamics simulations. Eleven publications co-authored by the principal investigators and Natick personnel resulted from this collaborative research.

  Two awards were received during the project period. The University of Connecticut received the 1998 *Commander's Educational Award for Excellence* from the U.S. Army Soldier Systems Command (SSCOM) for significantly advancing SSCOM's airdrop modeling capability. Co-authors from Natick and the University of Connecticut received a *Best Papers Award* at the $21^{st}$ Army Science Conference.

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- K. Stein, R. Benney, V. Kalro, T. Tezduyar, J. Leonard, and M. Accorsi, "Parachute Fluid Structure Interactions: 3-D Computation," *Computer Methods in Applied Mechanics and Engineering* (in press).
- M. Accorsi, R. Benney, J. Leonard, and K. Stein, "Structural Modeling of Parachute Dynamics," *AIAA Journal* (in press).
- R. Benney, K. Stein, W. Zhang, M. Accorsi and J. Leonard, "Controllable Airdrop Simulations Utilizing a 3-D Structural Dynamics Model," 15$^{th}$ CEAS/AIAA Aerodynamic Decelerator Systems Technology Conference, June, 1999, Toulouse, France.
- M. Accorsi, K. Lu, J. Leonard, R. Benney and K. Stein, "Issues in Parachute Structural Modeling: Damping and Wrinkling," 15$^{th}$ CEAS/AIAA Aerodynamic Decelerator Systems Technology Conference, June, 1999, Toulouse, France.
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- Jenkins, C.H. and Faisal, S.M. (1999). "Thermal Load Effects on Precision Membranes," *6th AIAA/ASME/AHS Adaptive Structures Forum at the 40th Structures, Structural Dynamics, and Materials Conference (AIAA/SDM).*

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## 7. SCIENTIFIC PERSONNEL

- Principal Investigators

  Professor John W. Leonard, University of Connecticut
  Professor Michael L. Accorsi, University of Connecticut
  Professor Christopher H. Jenkins, South Dakota School of Mines and Technology

- Graduate Students (Degree & Completion Date)

  Mr. Kun Lu, University of Connecticut (Ph.D., August 1999)
  Mr. Xinxiang Liu, South Dakota School of Mines and Technology (Ph.D., July 1999)

## 8. INVENTIONS

- No inventions were conceived during this research project.

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13. O.C. Zienkiewicz and R.L. Taylor, *The Finite Element Method, Volume 1: Basic Formulations and Linear Problems*, Fourth Edition, McGraw Hill Book Company, 1989, Section 14.3.

## 10. APPENDIX A: Selected Results from Numerical Simulations

- **Square Airbag Inflation Problem:** This example shows a comparison between the inflated shapes of a square airbag obtained with and without the wrinkling algorithm. The predicted shapes are extremely different. Examination of the stresses show that the solution obtained without wrinkling contains large compressive principal stresses. The predicted solution with wrinkling has no compressive stresses and is intuitively more correct.

- **C-9 Inflation Problem:** This example shows a comparison between the shapes of a round canopy parachute undergoing inflation obtained with and without the wrinkling algorithm. The canopy is initially in a highly folded unstressed configuration. The shape at three different times during inflation are shown. The results obtained using wrinkling are physically more correct than those obtained without wrinkling. These results clearly demonstrate that wrinkling is extremely important in parachute simulations.

- **Wrinkling of Isotropic and Orthotropic Disk:** This example shows the principal stress vectors for an annular membrane which is twisted in plane. Results are given for an isotropic and orthotropic membrane. For both cases, the wrinkling algorithm is used. The predicted stress distributions for these two cases are extremely different indicating that material orthotropy has a strong effect on the internal stress distribution.

- **Falling Ribbon Problem:** This example shows the transient response of a initially square ribbon subjected to constant internal pressure which falls under the influence of gravity. Three sets of results are given which correspond to (ND) No Damping, (FD) Fold Damping, and (MPD) Mass Proportional Damping. The ND and FD cases fall at the correct rate, whereas the MPD case is damped out and fails to fall. The time history of the velocity for the FD case is much smoother than the ND case demonstrating that the fold damping effectively damps spurious accelerations without effecting the global motion. The time step used for the FD case was ten times larger than the ND case indicating that the fold damping effectively stabilizes the solution which significantly reduces the computations required for the simulation.

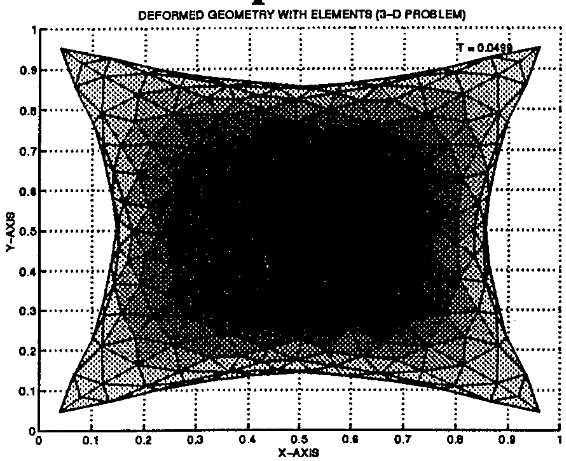
- **Simple Square Canopy Problem:** This example shows the transient response of a simple parachute using kink and fold damping (KFD) and no damping (ND). The parachute consists of a square canopy with four suspension lines. The same time step is used for the KFD and ND cases. For the KFD case, the canopy opens smoothly and a stable inflated shape is achieved. For the ND case, the opening is highly chaotic and the numerical simulation becomes unstable. This simulation demonstrates that the kink and fold elements effectively stabilize the solution during the initial opening phase.

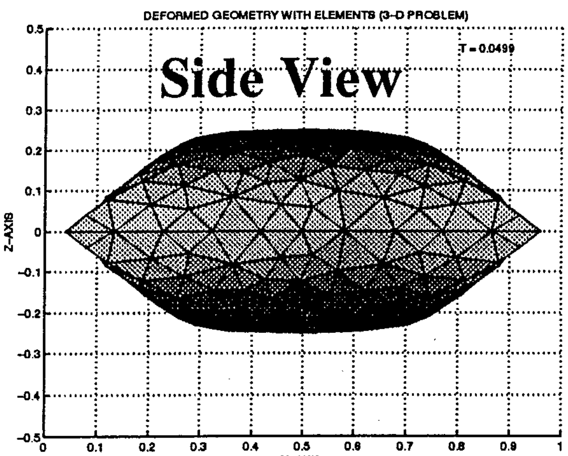
- **T-10 Inflated Shape and Maximum Principal Stress Contours:** This example shows how the principal stresses can be evaluated and displayed for various parachute simulations.

# Square Airbag Inflation Problem

## Wrinkling

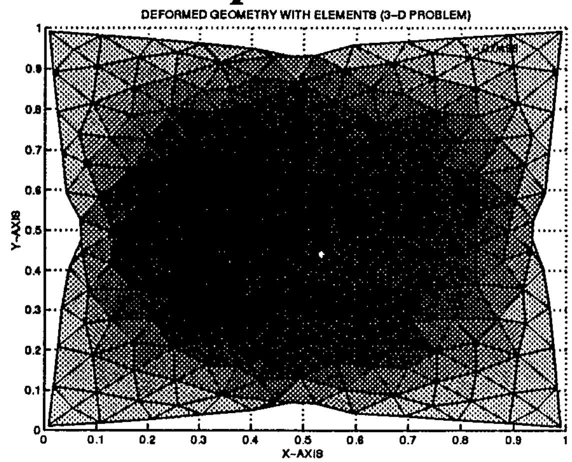
### Top View

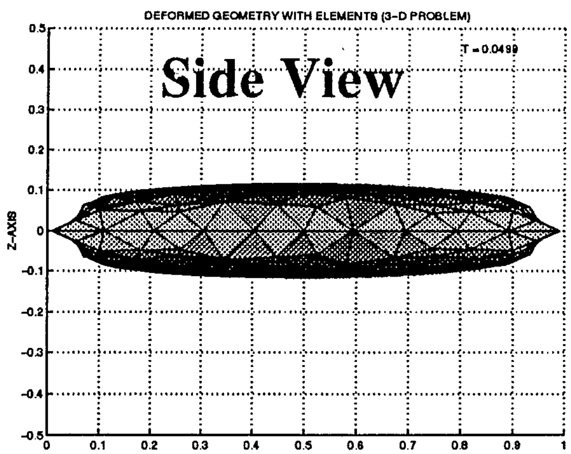


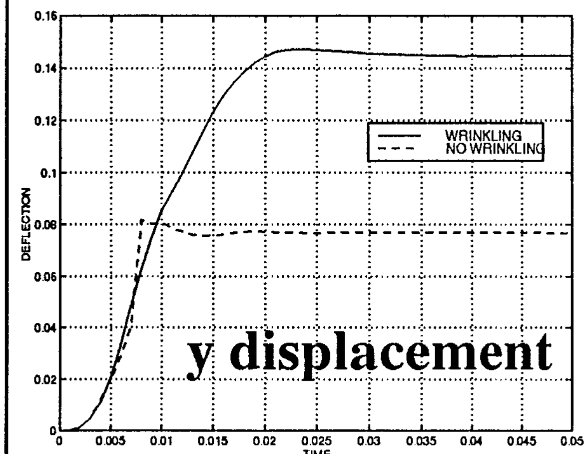

## No Wrinkling

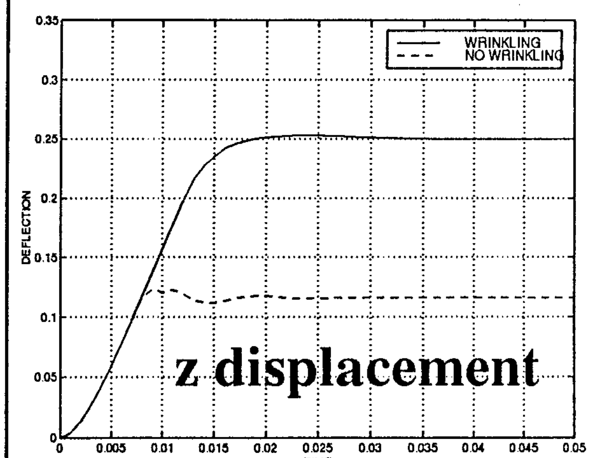
### Top View



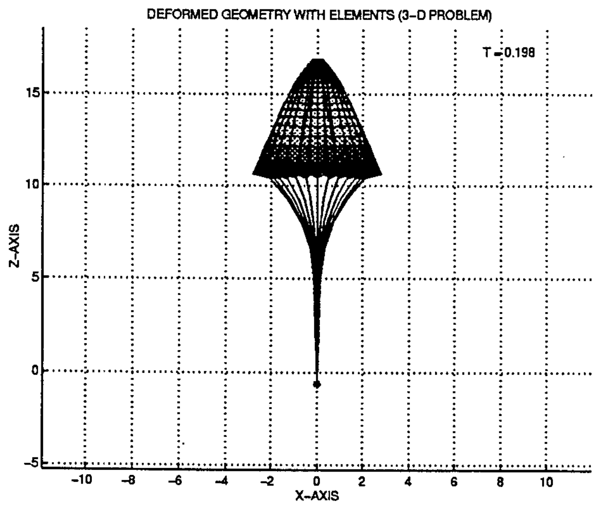

## Comparison

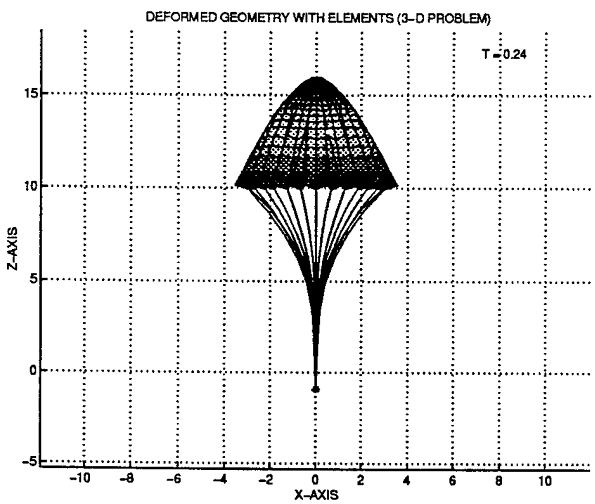


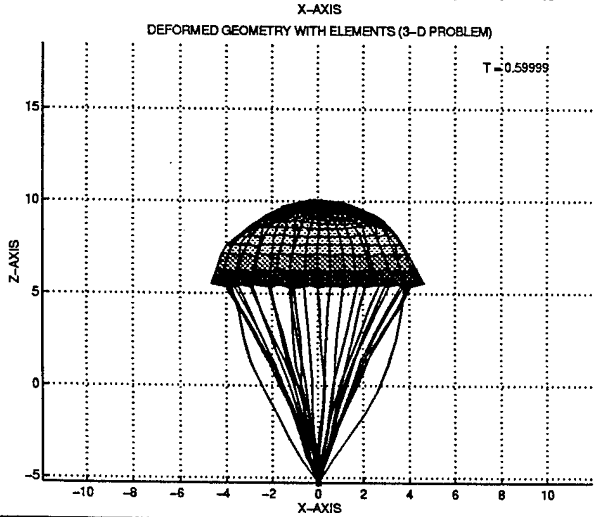



# C-9 Inflation Problem

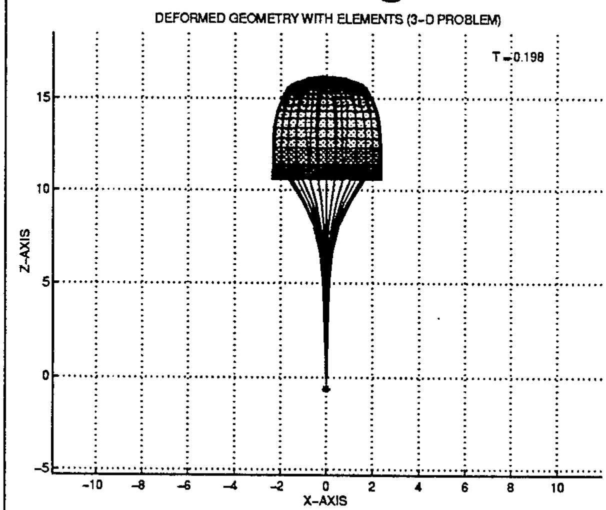
## No Wrinkling

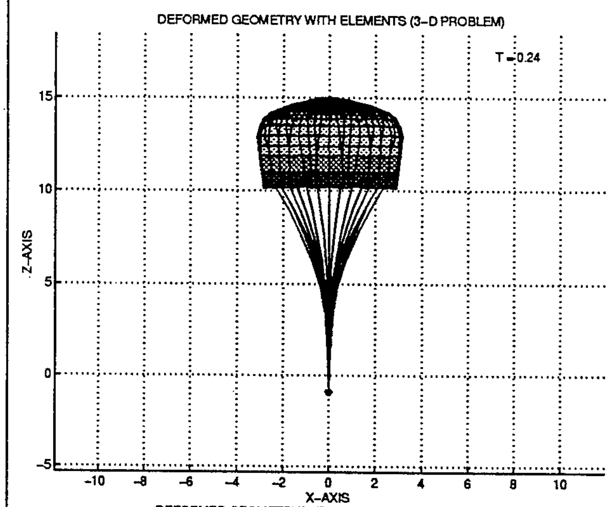


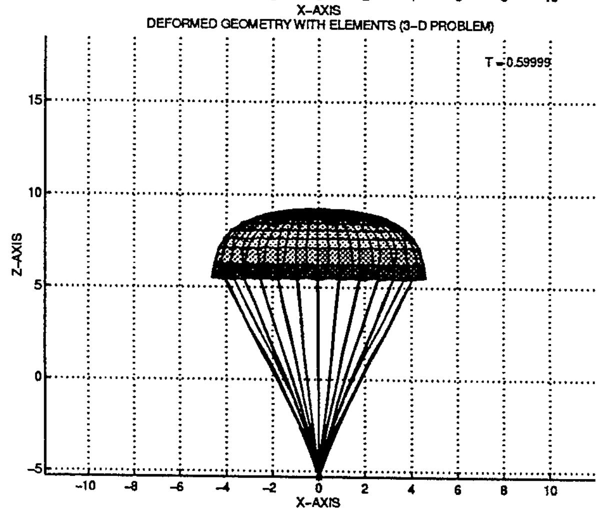



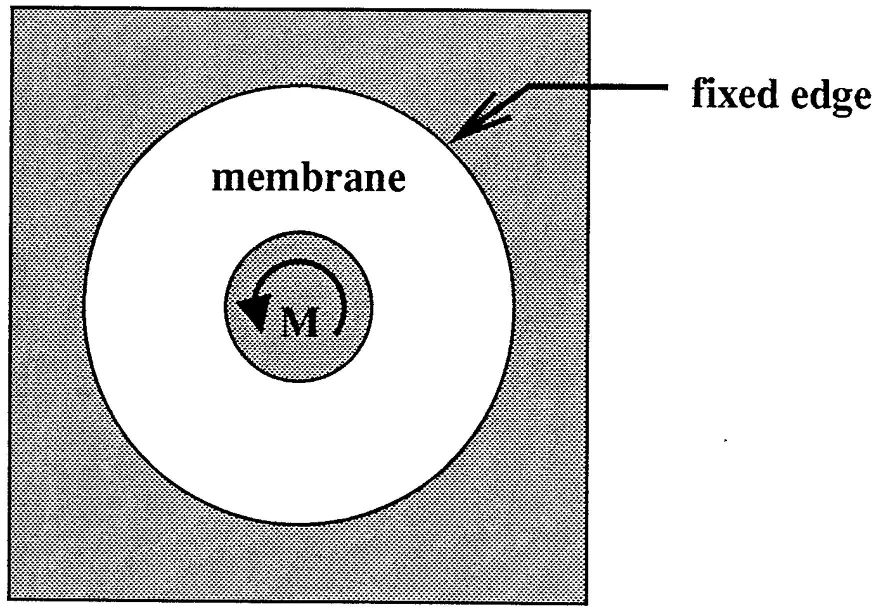

## Wrinkling

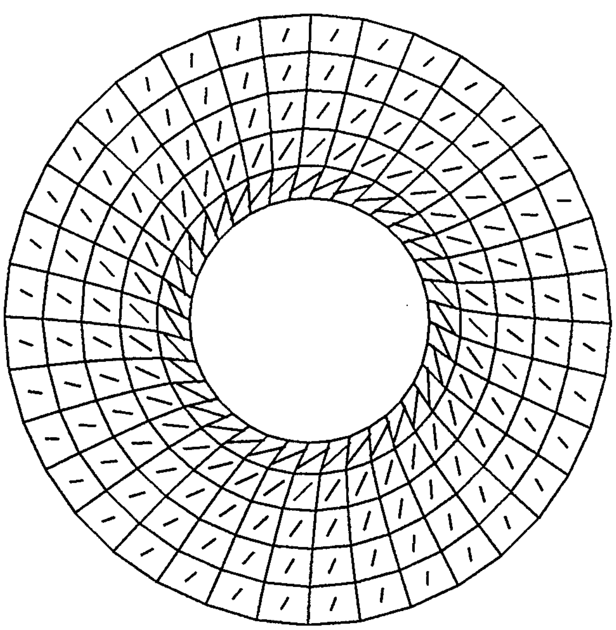


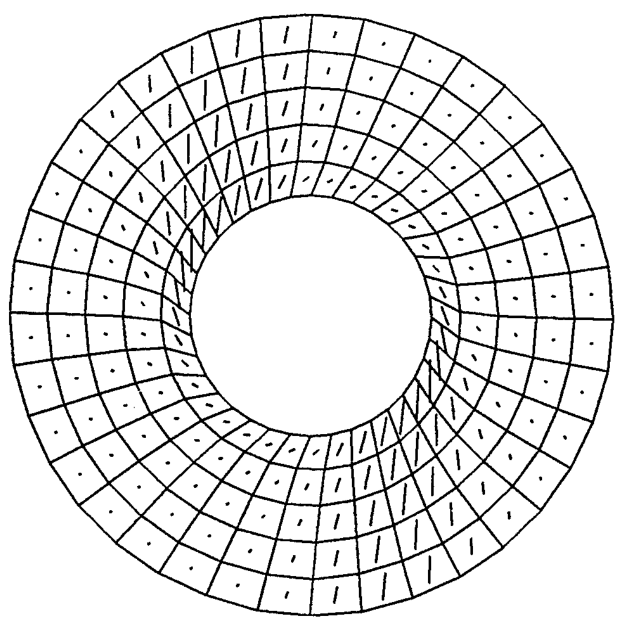



# Wrinkling of Isotropic and Orthotropic Disk.



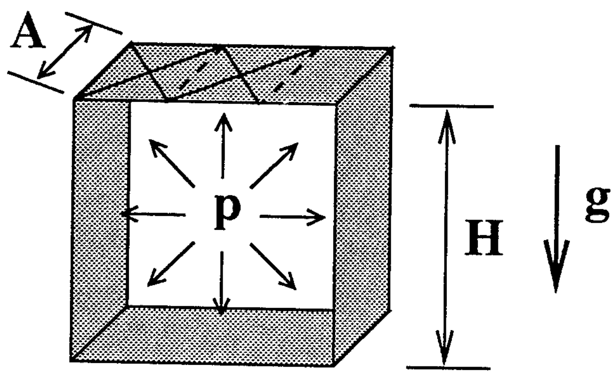
Principal Stress Vectors
Isotropic Membrane



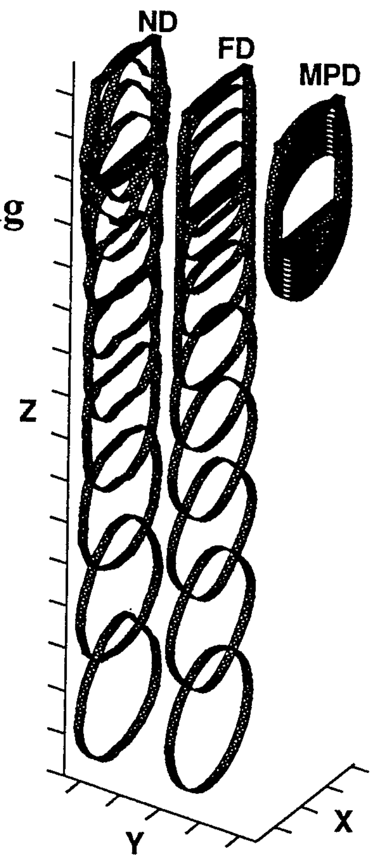
Principal Stress Vectors
Orthotropic Membrane

# Falling Ribbon Problem

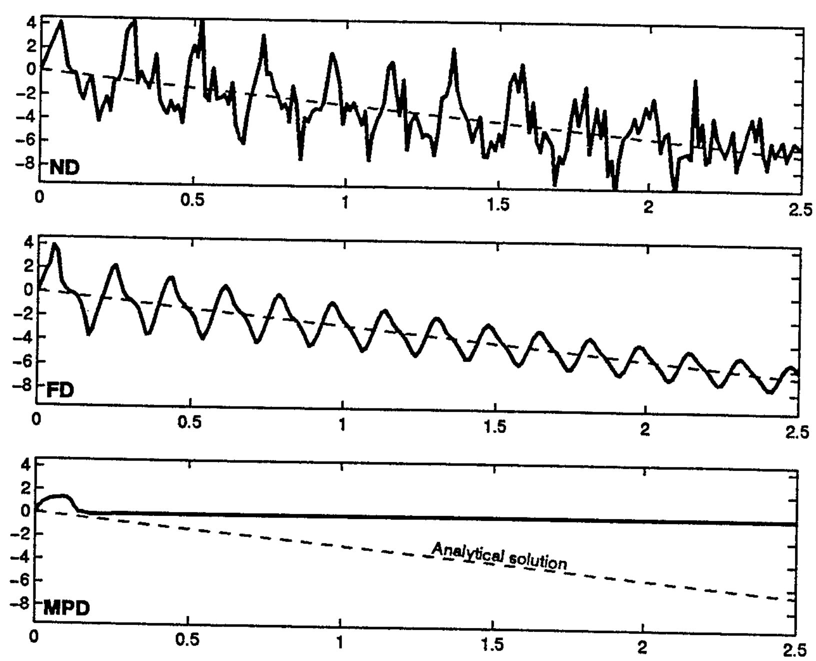
**ND = No Damping**
**FD = Fold Damping**
**MPD = Mass Proportional Damping**




Definition Sketch of Falling Ribbon.

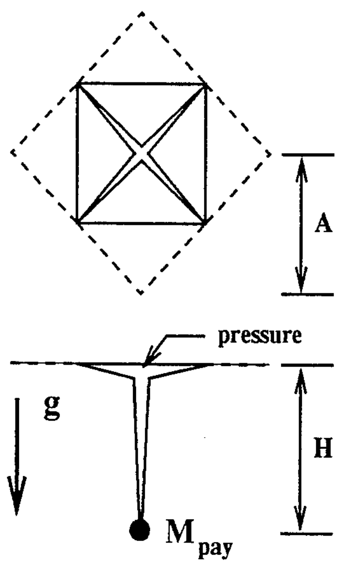



Ribbon Configurations at Selected Times.

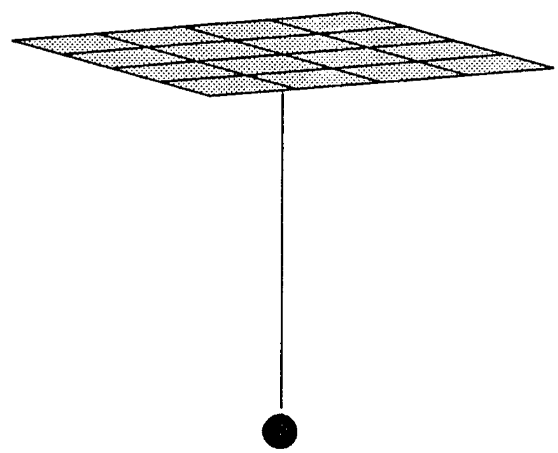



Time Histories of Ribbon Velocity.

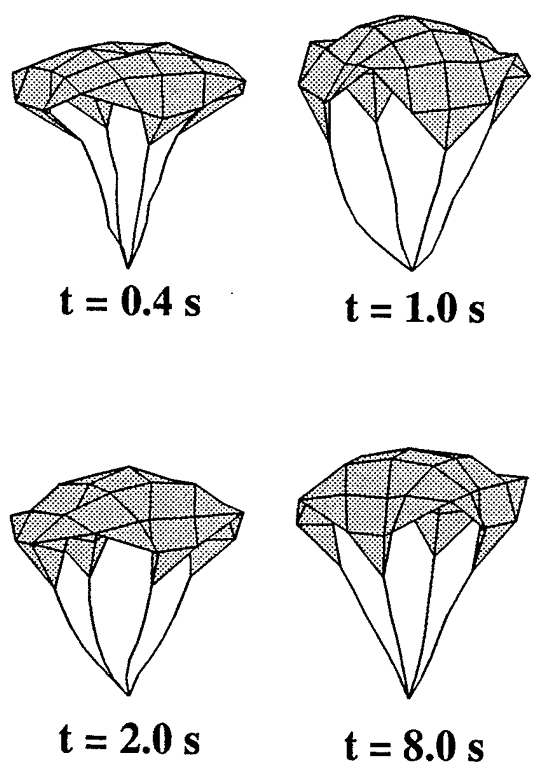
# Simple Square Canopy Problem



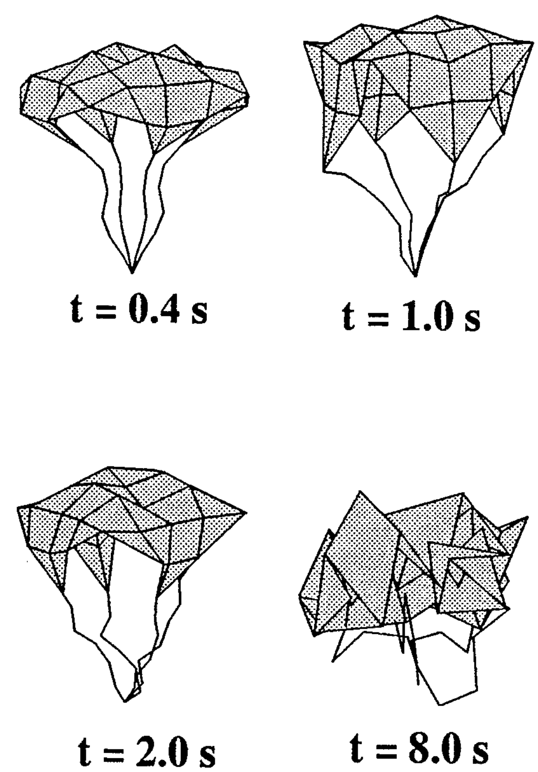

Definition Sketch of Initial Canopy Shape.



Finite Element Model of Initial Configuration.




Canopy at Select Times with Kink & Fold Damping




Canopy at Select Times with No Damping

# T-10: Inflated Shape and Maximum Principal Stress Contours